INTRODUCTION TO THE NOVA TECHNICAL CONTRACT

J. D. Lindl

J. D. Kilkenny

The 1990 National Academy of Sciences (NAS) final report[1] recommended proceeding with the construction of a 1- to 2-MJ Nd-doped glass laser designed to achieve ignition in the laboratory (a laser originally called the Nova Upgrade, but now called the National Ignition Facility, or NIF, and envisioned as a national user facility). As a prerequisite, the report recommended completion of a series of target physics objectives on the Nova laser in use at the Lawrence Livermore National Laboratory (LLNL). Meeting these objectives, which were called the Nova Technical Contract (NTC), would demonstrate (the Academy committee believed) that the physics of ignition targets was understood well enough that the laser requirements could be accurately specified. Completion of the NTC objectives was given the highest priority (it was Recommendation 1.1) in the NAS report. The NAS committee also recommended a concentrated effort on advanced target design for ignition. As recommended in the report, completion of these objectives has been the joint responsibility of LLNL and the Los Alamos National Laboratory. Most of the articles in this issue of the *ICF Quarterly* were written jointly by scientists from both institutions.

Several of the NTC objectives required the completion of improvements to Nova's power balance and pointing accuracy and of new diagnostics and new target fabrication capabilities. These improvements were called "Precision Nova" and are documented in Ref. 2.

The original NTC objectives have been largely met. This Introduction summarizes those objectives and their motivation in the context of the requirements for ignition. The articles that follow describe the NIF ignition target designs and summarize the principal accomplishments in the various elements of the NTC. Reference 3 gives a much more extensive discussion of ignition requirements.

Ignition Requirements

The strong connection between the compression achievable in a spherical implosion and the ignition threshold was pointed out by Nuckolls et al.[4] in 1972. Because the compression that can be achieved in an implosion is related to the implosion velocity v_{imp}, the ignition threshold depends strongly on v_{imp}. If a laser pulse shape can be achieved that maintains compressibility independent of v_{imp}, the ignition threshold varies[3,5] as v_{imp}^{-n}, where $n \approx 5$ for the target type shown in Fig. 1.

The implosion of a shell such as that shown in Fig. 1 is driven by the ablation of material from the surface of the shell and can be described by a spherical rocket equation. The work W done on the imploding shell is given by $W = \int P\, dV$, where P is the pressure generated by ablation and V is the volume enclosed by the shell. For a given shell mass, the implosion velocity is maximized by generating the highest possible ablation pressure on a shell that encloses the greatest possible volume.

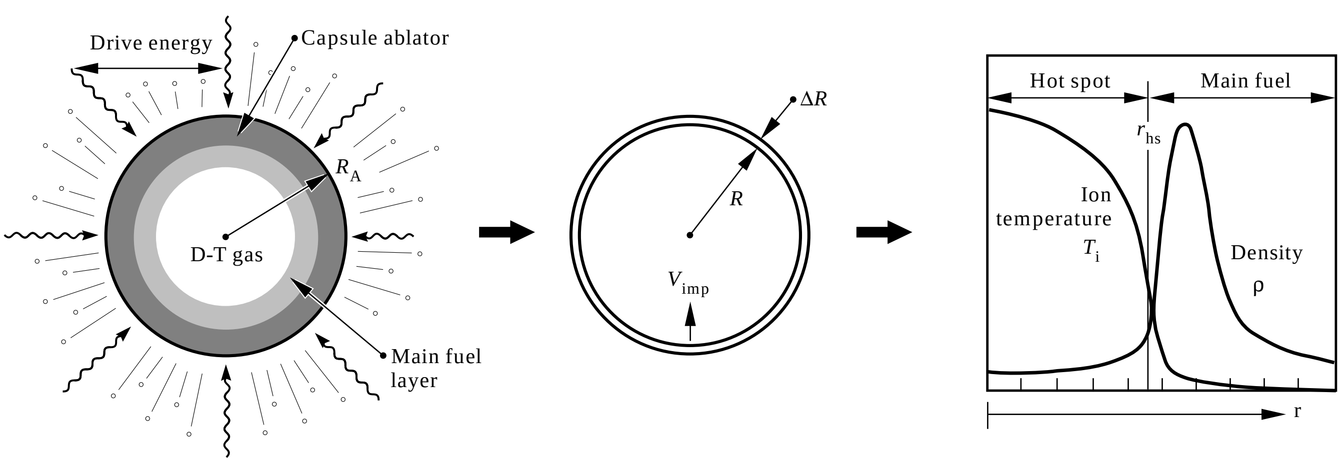
The ablation pressure is related to the energy flux incident on the surface of the shell. In laser-driven inertial confinement fusion (ICF), laser–plasma interaction effects limit the incident flux to ~10^{15} W/cm^2. In ion beam–driven ICF, the pressure is limited by the focused intensity achievable. In general, ablation pressures are limited to about 100 Mbar.

As the volume enclosed by a shell with fixed mass and density (and thus with a fixed volume of shell material) is increased, the shell must become thinner. Hydrodynamic instabilities during the acceleration and deceleration phases of the implosion limit the so-called in-flight aspect ratio to $R/\Delta R < 25$–35, where R = shell radius and ΔR = shell thickness as it implodes. For thin shells, the shell aspect ratio increases linearly with the volume enclosed. This limitation on shell aspect ratio, and the pressure limitation described above, together limit implosion velocities. If driver technology can be developed so that other details of an implosion, such as pulse shaping and pulse symmetry, can be controlled, these two limitations ultimately set the ignition threshold for laboratory fusion to a driver of about 1 to 2 MJ for capsules with implosion velocities of 3 to 4×10^7 cm / s.

As shown in Fig. 2, two principal approaches are used with lasers to generate the energy flux required to drive the implosion. In the direct-drive approach, the laser beams are aimed directly at the target. The beam energy is absorbed by electrons in the target's outer, low-density corona, and they transport that energy to the denser shell material to drive the ablation and the resulting implosion. In the indirect-drive approach, the laser energy is absorbed and converted to x rays by high-Z material inside the hohlraum that surrounds the target. The NTC has concentrated on indirect drive.

Because of the x-ray conversion and transport step, indirect drive is less efficient than direct drive. However, ablation driven by electron conduction is in general more hydrodynamically unstable than ablation driven by x rays.[3] (Indirect drive is less sensitive to hydrodynamic instability because x rays generate a higher ablation rate than electrons.) Measures taken to mitigate hydrodynamic instability in direct-drive targets[3,6] largely offset the efficiency advantage. Also, direct-drive targets are very sensitive to intensity variations within individual beams. These variations imprint perturbations on the target that are then amplified by hydrodynamic instability. If adequate beam uniformity can be achieved, calculations for current target designs[6] indicate that direct-drive targets have about the same ignition threshold as indirect-drive targets, but that they can have about a factor of 2 higher gain. The NIF will be configured with a beam geometry capable of being used for either direct or indirect drive.[3] Beam smoothing and hydrodynamic instability requirements for direct drive will be determined in an implosion physics program on the Omega Upgrade laser at the University of Rochester and in planar experiments on Nova and on the Nike laser at the Naval Research Laboratory.

Although indirect drive is less sensitive to individual beam nonuniformities than direct drive, beam placement inside the hohlraum must be accurately controlled to achieve adequate symmetry. As indicated in Fig. 1, typical capsule convergence ratios are $C_r = R_A / r_{hs} \approx 25–35$, where R_A is the initial outer capsule radius and r_{hs} is the final compressed hot fuel radius (the "hot spot" radius). Achieving a convergence ratio this high requires x-ray fluxes uniform to 1 to 2%. Use of a relatively large hohlraum (with a ratio of hohlraum radius to capsule radius of 3–4) greatly reduces imbalances in irradiation between points close together on the capsule surface;[3,7] imbalances between points farther apart can be controlled by hohlraum geometry and laser beam placement. In the NIF laser, two rings of beams, each with an independent pulse shape, will enter each end of the hohlraum. (In Nova, a single ring



Driver–target coupling
$\Rightarrow I_r \lesssim 10^{15}$ W / cm^2 or $\lesssim$300 eV

To control:
- Absorption / preheat
- X-ray conversion
- Transport / drive

Symmetry:	$\frac{R_A}{r_{hs}}$ =	Convergence ratio	$\approx$ 20–35 $\Rightarrow$	Coupling $\eta \approx$ 10–15%
Stability:	$\frac{R}{\Delta R}$ =	In-flight aspect ratio	$\approx$ 25–35 $\Rightarrow$	$I_R \gtrsim 4 \times 10^{14}$ W / cm^2 or 250 eV Surface <1000 Å
Ignition:	• $T_{i,\,hs}$ = 10 keV • $\rho r_{hs} \approx 0.3$ g / cm		$\Rightarrow$	V_{imp} 3–4 $\times 10^7$ cm / s for E_{driver} = 1–2 MJ

FIGURE 1. Physics specifications on current ICF ignition targets include constraints on drive intensity, symmetry, stability, and ignition. (02-08-0692-1865Cpb02)

of five beams enters each end.) The two rings will allow "beam phasing," in which the power in the individual rings is varied independently to control time-dependent asymmetry. For a short-wavelength laser such as Nova (or NIF) (laser wavelength $\lambda = 0.35$ µm in most experiments), about 70% of the incident laser energy is converted to x rays by the high-Z hohlraum material, but symmetry requirements limit overall coupling efficiency to 10 to 15% of the laser energy into the capsule for typical ignition designs.

Since the hohlraum wall physics and the capsule physics are essentially the same for any x-ray source, much of what is learned on Nova is also applicable to ion-beam drivers. Because of this, Sandia National Laboratories has been able to carry out experiments on Nova to test pulse-shaping schemes important in light-ion-driven targets. Indirect-drive laser experiments also provide much of the target physics basis for the Heavy Ion Driver Program, supported by the DOE Office of Fusion Energy.

The laser requirements for ignition by indirect drive can be shown in a plot of laser power P_L vs laser energy (Fig. 3). As laser power increases for a given laser energy, the achievable hohlraum temperature T_R increases. The ablation pressure increases approximately[3] as $T_R^{3.5}$, so v_{imp} is a strong function of T_R. Generation of plasma in the hohlraum increases as T_R increases; this results in laser–plasma collective effects that limit T_R and the usable power that can be put into the hohlraum. This power depends on laser wavelength, laser beam spatial and temporal uniformity, pulse duration, hohlraum size, and other variables. At $T_R = 400$ eV, for the long pulses required for ignition capsules, the hohlraum plasma density n will approach $n/n_c \approx 1/4$ (the critical density $n_c = 10^{21}\,\lambda^{-2}$ cm^{-3}, where λ is the

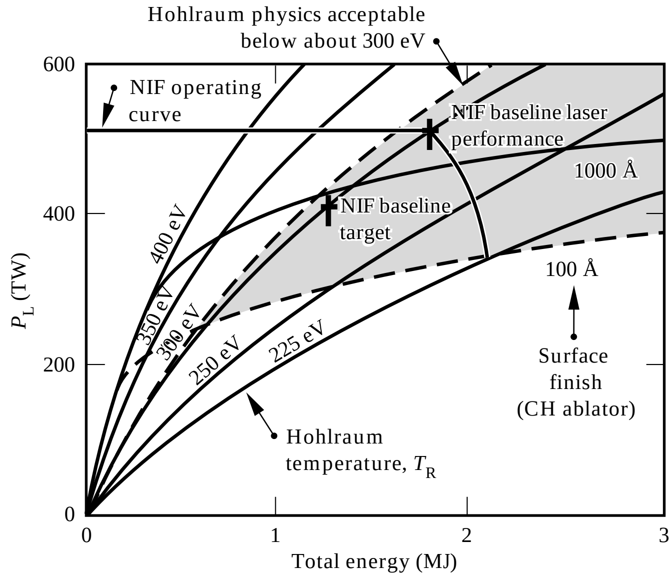


FIGURE 3. For laser-driven indirect-drive ignition targets, plasma physics issues constrain the achievable hohlraum temperature, and hydrodynamic instabilities (represented here by surface finish) establish the minimum required temperature at a given driver energy. The shaded region constitutes the accessible region in power–energy space where ignition with indirect-drive capsules is predicted. The NIF power–energy operating curve shown here has ample margin. (08-00-0693-2196Dpb01)

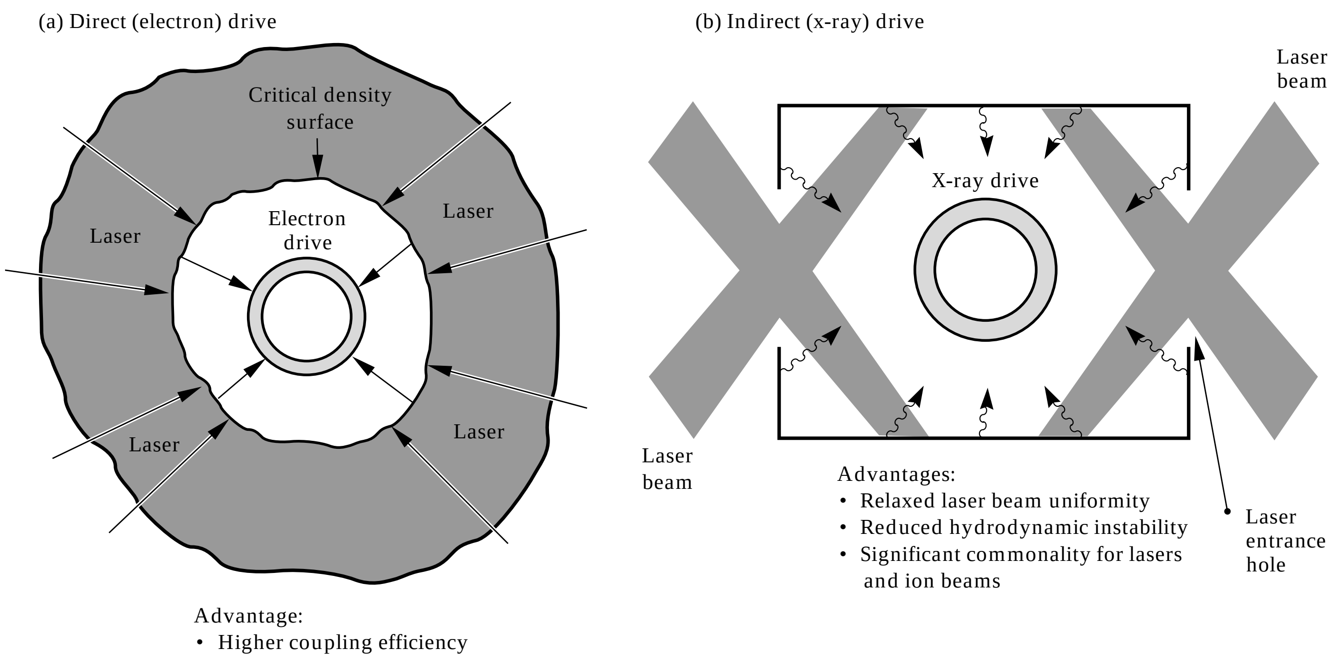


FIGURE 2. ICF uses either (a) electron conduction (direct drive) or (b) x rays (indirect drive) to produce a high shell ablation pressure to drive an implosion. (08-00-0894-3312Apb01)

laser wavelength in micrometers). Experiments[3] at $\lambda = 1$ µm suggest that this is an upper-limit temperature for ignition hohlraums. (It should be possible to achieve higher temperatures for short pulses with reduced plasma filling.) We limit peak hohlraum temperatures in current ignition target designs to $T_R \approx 300$ eV, which limits plasma densities to $n/n_c \approx 0.1$. Above this temperature, it is likely that a significant fraction of laser light would be scattered out of the hohlraum or be absorbed in a way that results in the production of high-energy electrons that heat the fusion fuel and thereby reduce the achievable compression.

At a given driver energy, hydrodynamic instabilities place a lower limit on the temperature required to drive a capsule to ignition conditions. A larger capsule requires a lower implosion velocity, which can be achieved with a lower radiation temperature consistent with the shell aspect ratio constraints. The value of the required minimum temperature at a given energy will depend on the allowed shell aspect ratio, which depends on the smoothness of the capsule surface, currently limited to 200 to 300 Å rms for Nova capsules. Below a certain size, the required implosion velocity will exceed the velocity achievable within the temperature and capsule uniformity constraints, and ignition is not possible. Above this threshold energy, there is a region in power–energy space where ignition is feasible. This is the shaded area in Fig. 3, which encloses the region limited by 300-eV hohlraum temperatures and 100-Å capsule surface finishes.

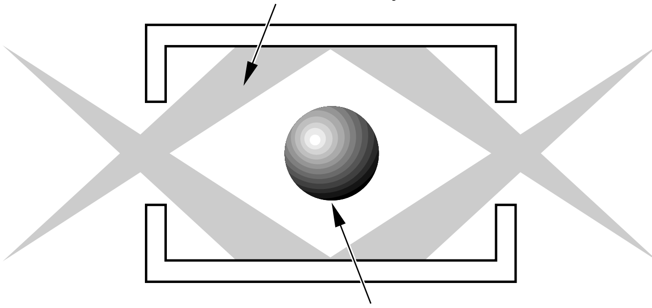


FIGURE 4. The Nova program comprises two elements that address the hohlraum and capsule physics of ignition and high gain: hydrodynamically equivalent physics (HEP) and hohlraum laser–plasma physics (HLP). (05-00-0995-2136pb01)

The NIF laser is being designed to operate at an energy of 1.8 MJ and a power of 500 TW; both values are about a factor of 2 above the threshold ignition values shown in Fig. 3, allowing for remaining uncertainty in the implosion process. Within the ignition region shown in Fig. 3, a wide variety of targets have been evaluated, as discussed in the article "Ignition Target Design for the National Ignition Facility," p. 215. The predicted yields of these targets range from about 1 to greater than 25 MJ.

Elements of the Nova Technical Contract

The objectives of the NTC have been to experimentally demonstrate and predictively model laser–plasma interaction, hohlraum characteristics, and capsule performance in targets that have been scaled in key physics variables from NIF targets. Since the Nova geometry consists of a single ring of five beams in each end of the hohlraum, Nova experiments have been limited to controlling only the time-averaged symmetry. To address the hohlraum and hydrodynamic constraints on indirect-drive ignition, the NTC comprises so-called Hydrodynamically Equivalent Physics (HEP) goals and Hohlraum Laser–Plasma Physics (HLP) goals, as shown in Fig. 4.

The HEP program addresses capsule physics issues associated with ignition. These include hydrodynamic instability in planar and spherical geometries, the effects of drive nonuniformity on capsule performance, and the physics associated with ignition (energy gain and energy loss to the fuel) in the absence of α-particle deposition. The HEP program was subdivided into five subgoals:

- HEP1: Demonstrate fuel densities of 20 to 40 g/cm^3 using high-contrast pulse shaping with noncryogenic targets. The fuel density will be inferred from measurements of fuel areal density ρR using advanced neutron-based diagnostics.
- HEP2: Measure the reduced linear growth and early nonlinear behavior of the Rayleigh–Taylor (RT) instability at the ablation surface for x-ray-driven targets. Using planar targets, observe single-mode growth at the ablation surface by factors of >30, from which reductions by factors of 2 to 3 from the classical RT growth rate are inferred. Targets of various compositions will be used to confirm the modeling of plasma opacity as it affects x-ray-driven hydrodynamics.
- HEP3: Using x-ray spectroscopy, demonstrate pusher/fuel mixing that is dependent on initial target surface quality. The targets will be low-growth (perturbations grow by a factor of ~10), low-convergence ($C_r < 10$) plastic capsules with a multimode spectrum of initial surface perturbations.

- HEP4: Demonstrate quantitative understanding of implosion experiments to convergence ratios $C_r \approx 10$ with overall hydrodynamic instability growth factors of 100 to 500 for an l-mode spectrum similar to those characteristic of ignition target designs (for which maximum growth occurs for mode numbers $l \approx 30$).
- HEP5: Extend HEP4 experiments to convergence ratios $C_r = 20$–40 with capsule performance consistent with Nova's symmetry limitations.

The HLP program addresses laser–plasma coupling, x-ray generation and transport, and the development of energy-efficient hohlraums that provide the appropriate spectral, temporal, and spatial x-ray drive. The HLP program was divided into seven subgoals:

- HLP1: Demonstrate acceptable coupling of laser light to x rays in low-Z-lined hohlraums using shaped laser pulses and peak radiation temperatures up to $T_R \approx 210$ eV.
- HLP2: Demonstrate acceptable coupling of laser light to x rays in lined hohlraums with peak radiation temperature $T_R \geq 270$ eV with 1-ns square pulses. Acceptable coupling for HLP1 and 2 was defined as follows:
  - — Absorption fraction $f_{abs} > 90\%$.
  - — Stimulated Brillouin scattering fraction $f_{SBS} < 5$–10%.
  - — Suprathermal-electron fraction $f_{hot} < 5\%$ at $T_{hot} \geq 50$ keV.
  - — Stimulated Raman scattering fraction $f_{SRS} < 5\%$.
- HLP3: Demonstrate an ability to measure and calculate energy balance in a hohlraum with emphasis on wall loss and albedo and an ability to diagnose and predict the (time-dependent) position of the laser-produced x-ray source within the hohlraum. Demonstrate an ability to characterize and model plasma evolution in a hohlraum.
- HLP4: Demonstrate symmetry control with low- and intermediate-Z-lined hohlraums. Achieve low-order l-mode (P_2, P_4) time-integrated symmetry ≤2–4%.
- HLP5: Demonstrate acceptable levels of scattering in large-scale plasmas that match the plasma conditions, beam geometry, and beam smoothing of ignition hohlraums as closely as possible. The plasmas should have density and velocity scalelengths ~2 mm, electron temperature >1.5 keV, and $n / n_c < 0.15$. Acceptable levels of scattering were defined as follows:
  - — Stimulated Brillouin scattering fraction f_{SBS} (back, side) < 5–10%.
  - — Stimulated Raman scattering fractions f_{SRS} (back, side) < 5–10% and f_{SRS} (forward) < 5%.
- HLP6: Evaluate the impact of laser beam filamentation on SBS and SRS and develop control techniques to the extent necessary to ensure acceptable levels of scattering.
- HLP7: Develop an improved understanding of x-ray conversion efficiency in hohlraums under conditions appropriate for NIF ignition targets.

Table 1 shows where each NTC element is discussed in detail in this *Quarterly*. The degree to which convergence ratio can be increased on Nova for HEP5 is yet to be determined. The appendix gives a more detailed statement of the objectives of the NTC as presented at the 1990 NAS Review. Because of the declassification of many aspects of ICF in 1993, the appendix includes many details, such as specific hohlraum temperature goals, left out of the unclassified summary contained in the NAS report. These goals have served as a very valuable guide to the Nova Target Physics Program for the past five years, and have largely been carried out as specified.

Changes to the NTC Objectives and Plans for Further Work on Nova

One notable change to the Nova targets has been made as we have learned from the results of more detailed NIF target designs. Ignition-scale hohlraums require some sort of a low-Z fill to control the position of laser beam absorption and x-ray emission. At the time of the NAS report, ignition targets used low-Z liners on the inside of the hohlraum wall to create this plasma. These "lined hohlraum" targets, spelled out in the NTC, worked well in the Nova experiments

TABLE 1. List of NTC elements in this *Quarterly*.

Subgoal discussion	Article title	Page no.
HEP:		
• HEP1	Indirectly Driven, High-Convergence Implosions	226
• HEP2	Planar and Cylindrical Rayleigh–Taylor Experiments on Nova	232
• HEP3	Diagnosis of Pusher–Fuel Mix in Indirectly Driven Nova Implosions	265
• HEP4	High-Growth-Factor Implosions	271
HLP:		
• HLP1, HLP2, and HLP7	Energy Coupling in Lined Hohlraums	281
• HLP3 and HLP4	Nova Symmetry: Experiments, Modeling, and Interpretation	293
• HLP5 and HLP6	Laser–Plasma Interactions in NIF-Scale Plasmas	305
Appendix	Nova Technical Contract as presented to the 1990 NAS Review of ICF	A-1

described below. But detailed NIF target calculations predicted a significant asymmetric pressure pulse on the capsule when the liner plasma collapsed onto the hohlraum axis. Although this pulse may have been an artifact of calculations that are currently constrained to be axisymmetric, the baseline NIF target design has been switched from a liner to a low-*Z* gas fill. Symmetry control with gas-filled targets has been demonstrated on Nova, but the experiments are still in progress and will not be described here.

Continuing work aimed at gaining further understanding of ignition targets is covered under a set of goals called the Target Physics Contract, which are extensions of goals in the NTC. Most of these goals should be reached within about a year.

HEP2 has been extended to include direct measurement of perturbation growth in spherical and/or cylindrical geometry and demonstration of a quantitative understanding of the three-dimensional (3-D) evolution of the RT instability. This objective has included the development of 3-D radiation hydrodynamics codes, which are now used in the planning and evaluation of experiments.

HEP4 and HEP5 are continuing, with emphasis on 3-D calculations of the effects of capsule surface and hohlraum flux perturbations on capsule performance. Target designs that minimize the flux asymmetry are being evaluated to determine the limits to the achievable convergence ratio on Nova.

The goals of the HLP program, including energetics, x-ray emission pattern and hohlraum-wall blowoff, and symmetry have been extended to include gas-filled hohlraums. HLP5 and HLP6 will continue to explore the limits to hohlraums imposed by laser–plasma interaction with various forms of laser-beam coherence control.

Notes and References

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